Three-phase Voltage-fed Quasi-Z-Source AC-AC Converter

Xupeng Fang, Guanzhong Gao, Lixin Gao and Bolong Ma

Abstract—The paper proposes a novel three-phase voltage-fed quasi-Z-source ac-ac converter topology to overcome the shortcomings of the traditional three-phase AC-AC chopper. The quantitative relationship between the output voltage and duty-ratio is deduced by investigating the topology and operating principle. It can provide buck-boost function, and the output voltage of the circuit can keep stable in the case of voltage sagging. Simulation is performed using the MATLAB software, and the experimental circuit is built based on the simulation results, the simulation and experimental results verify the correctness and feasibility of the proposed ac-ac converter topology.

Index Terms — Buck-boost, duty-ratio, quasi-Z-source, three-phase AC-AC converter, voltage-fed.

I. INTRODUCTION

HE Z-source inverter topology was proposed by Professor Fangzheng Peng in 2001 [1], once it has been put forward, it has aroused widespread concern in the power electronics field and became a hotspot in the industry; it has been derived to the power conversion of rectification, AC voltage regulation, DC chopping [2-4]. However, there are some defects in the circuit. In 2008, Professor Fangzheng Peng proposed an improved circuit topology which is named the quasi-Z-source converter, it can overcome the problem of too large capacitor voltage or inductor current in the traditional Z-source converters. In the last 10 years, the research on the quasi-Z-source converter is in the ascendant, and according to the incomplete statistics, there have been over 1000 related papers published. Among them, in addition to the most articles about the quasi-Z-source inverters and their applications, the research of quasi-Z-source AC-AC converters is also one of the hotspots [5-23]. The quasi-Z-source AC-AC converter can not only realize direct AC-AC conversion, but also realize can flexible buck-boost function. It can overcome the disadvantages of the traditional phase controlled AC voltage regulator which can only buck the voltage and decrease the input power factor. It is also possible to overcome the

problem of short-circuit or open-circuit caused by the common mode conduction or common mode turn-off of the power switching devices in the traditional AC choppers. There are chopper circuit or matrix converter topologies in these circuit topologies [16-18]. The single phase voltage-fed quasi-Z-source converter has been studied 10, which can solve the problem of the traditional single-phase AC voltage regulator. Based on the single-phase voltage-fed quasi-Z-source ac-ac converter, its three-phase circuit version could be deduced. By PWM (Pulse Width Modulation) duty-ratio control, the power factor of the input side can be increased. Compared to the existing three-phase transformer, the quasi-Z-source-based ac-ac converter has unique features: low power loss, low noise, small size, controllable voltage, good output waveform and so on. The following is the structure of the manuscript: the second part is the analysis of the circuit structure, the operating principle and the small signal model of the presented converter, the third part gives the simulation results of the circuit, the fourth part gives the experimental results, and the fifth part gives the conclusions.

II. CIRCUIT STRUCTURE, OPERATING PRINCIPLE AND THE

SMALL SIGNAL MODEL

A. Circuit Structure

Fig.1 shows the presented three-phase voltage-fed quasi-Z-source ac-ac converter topology, it is composed of six parts, which are the bidirectional full controlled switches, quasi-Z-source network, the filter capacitors and inductors, power supply and the load. The quasi-Z-source network consists of six inductors, six capacitors, and three bidirectional full controlled switches. The bidirectional full controlled power switch is composed of two anti-series IGBT, the function of the quasi-Z-source network which composed of inductors and capacitors is energy storage and filtering, and it plays a key role in bucking or boosting voltages and power conversion. The synchronous PWM control method is used in the three-phase circuit, to ensure the three phase output voltage symmetry, each phase consists of two bidirectional full controlled switches turned on and off in complement (i. e, S_{x1} and S_{x2} in Fig.1, x=a, b, c). The regulation of the output voltage is realized by adjusting the duty-ratio of the power switch. The switches S_{x1} (x=a, b, c) are turned on and off synchronously, and at the same, the switches S_{x2} (x=a, b, c)

Manuscript was submitted for review on 27, October, 2017.

Xupeng Fang, Guanzhong Gao, Lixin Gao and Bolong Ma are with the College of Electrical Engineering and Automation, Shandong University of Science and Technology.(email: skdfxp@163.com, 994848330@qq.com, 371440520@qq.com, 371440520@qq.com).

Digital Object Identifier 10.30941/CESTEMS.2018.00041

are turned on and off synchronously.

Since the switching frequency is much higher than the power frequency, the power supply can be looked as the DC power within one switching period, and thus the output voltage is only related to the duty ratio D. The following analysis will base on the situation of symmetric load. The three-phase quasi-Z-source ac-ac converter has two working states: power switches S_{x1} are on and S_{x2} are off (state one), power switches S_{x2} are on and S_{x1} are off (state two).

B. Operating Principle

When the circuit is in working state one, that is, the power switches S_{x1} (x=a, b, c) are turned on, and the S_{x2} (x=a, b, c) are turned off, as shown in Fig. 2. we can see, the three phase load is in equilibrium, the potential of the neutral point of the three-phase load is equal to the potential of the neutral point of the three-phase power supply, thus the circuit can be equivalent to connect the neutral point of the three-phase power supply to the neutral point of the three-phase gower supply to the neutral point of the load, as shown in Fig. 3, since within one switching period the input voltage basically remains constant, so there are three loops, according to Kirchhoff voltage law, we have:

$$\begin{bmatrix} V_{a} \\ V_{b} \\ V_{c} \end{bmatrix} = \begin{bmatrix} V_{La1} \\ V_{Lb1} \\ V_{Lc1} \end{bmatrix} + \begin{bmatrix} V_{Ca1} \\ V_{Cb1} \\ V_{Cc1} \end{bmatrix}$$

$$\begin{bmatrix} V_{Ca2} \\ V_{Cb2} \\ V_{Cb2} \\ V_{Cc2} \end{bmatrix} = \begin{bmatrix} V_{La2} \\ V_{Lb2} \\ V_{Lc2} \end{bmatrix}$$

$$\begin{bmatrix} V_{Ca1} \\ V_{Ca1} \\ V_{Cb1} \\ V_{Cc1} \end{bmatrix} = \begin{bmatrix} V_{La2} \\ V_{Lb2} \\ V_{Lc2} \end{bmatrix} + \begin{bmatrix} V_{La3} \\ V_{Lb3} \\ V_{Lc3} \end{bmatrix} + \begin{bmatrix} V_{Za} \\ V_{Zb} \\ V_{Zc} \end{bmatrix}$$

$$\begin{bmatrix} V_{Ca1} \\ V_{Ca1} \\ V_{Ca1} \end{bmatrix} = \begin{bmatrix} V_{La2} \\ V_{Lb2} \\ V_{Lc2} \end{bmatrix} + \begin{bmatrix} V_{La3} \\ V_{Lb3} \\ V_{Lc3} \end{bmatrix} + \begin{bmatrix} V_{Za} \\ V_{Zb} \\ V_{Zc} \end{bmatrix}$$

Fig.1. The three-phase Z-source ac-ac converter topology.



Fig.2. The circuit structure of the operating state one.

When the circuit is in working state two, that is, the power switches S_{x^2} (x=a, b, c) are turned on, and the power switches S_{x1} (x=a, b, c) are turned off, as shown in Fig. 4. we can see, the three phase load is in equilibrium, the potential of the neutral point of the three-phase power supply, the potential of the neutral point of the load and the potential at the switches S_{x2} (x=a, b, c) are basically equal, which can be divided into two separate three-phase circuits, as shown in Fig. 5. Similarly, the power supply voltage basically remains constant in a switching period, so there are three loops, according to the Kirchhoff voltage law and we have,



Fig.3. The equivalent circuit of the operating state one.

$$\begin{bmatrix} V_{a} \\ V_{b} \\ V_{c} \end{bmatrix} = \begin{bmatrix} V_{La1} \\ V_{Lb1} \\ V_{Lc1} \end{bmatrix} - \begin{bmatrix} V_{La2} \\ V_{Lb2} \\ V_{Lc2} \end{bmatrix} + \begin{bmatrix} V_{Ca1} \\ V_{Cb1} \\ V_{Cb1} \\ V_{Cc1} \end{bmatrix} + \begin{bmatrix} V_{Ca2} \\ V_{Cb2} \\ V_{Cc2} \end{bmatrix}$$

$$\begin{bmatrix} V_{Ca1} \\ V_{Cb1} \\ V_{Cc1} \end{bmatrix} = \begin{bmatrix} V_{La2} \\ V_{Lb2} \\ V_{Lc2} \end{bmatrix}$$

$$\begin{bmatrix} V_{La3} \\ V_{Lb3} \\ V_{Lc3} \end{bmatrix} + \begin{bmatrix} V_{Za} \\ V_{Zb} \\ V_{Zc} \end{bmatrix} = 0$$

$$\begin{bmatrix} V_{La3} \\ V_{Lc3} \\ V_{Lc3} \end{bmatrix} + \begin{bmatrix} V_{Za} \\ V_{Zb} \\ V_{Zc} \end{bmatrix} = 0$$



Fig.4. The circuit structure of the operating state two.



Fig.5. The equivalent circuit of the operating state two.

From the above analysis, suppose the duty cycle of the power switches S_{x1} (x=a, b, c) are *D*, the period of ac power supply is *T*, the switching period of the power switches is T_s , the initial voltage value of L_{x1} and L_{x2} (x=a, b, c) are 0, and during a power supply period *T* the average voltage of the inductors L_{x1} and L_{x2} (x=a, b, c) will be 0. From the formulas (1) and (2), we can have

$$\frac{1}{T} \left[\sum_{i=1}^{n} \int_{t_{2i-2}}^{t_{2i-1}} (-V_x - V_{Cx2}) dt + \sum_{i=1}^{n} \int_{t_{2i-1}}^{t_{2i}} (-V_{Cx1} - V_x) dt \right] = 0$$

$$\frac{1}{T} \left[\sum_{i=1}^{n} \int_{t_{2i-2}}^{t_{2i-1}} (-V_x) dt + \sum_{i=1}^{n} \int_{t_{2i-1}}^{t_{2i}} (V_x - V_{Cx1} - V_{Cx2}) dt \right] = 0$$

$$D = \frac{t_{on}}{T_s}$$

And

$$T_{s} = t_{2i} - t_{2i-2}$$
$$t_{on} = t_{2i-1} - t_{2i-2}$$

 $T = t_{2n} - t_0$

From above, we have

$$-V_x + V_{Cx1}D - V_{Cx2}(1-D) = 0$$

- V_{Cx1}(1-D) + V_{Cx2}D = 0

Then

$$V_{Zx} = \frac{D}{2D - 1} V_x \tag{3}$$

By the formula (3), the relationship between the duty ratio D and the boost ratio B is shown in Fig. 6, which is divided into two work modes, the reverse buck-boost mode (D < 0.5) and the positive boost mode (D > 0.5).



Fig.6. The relationship between the duty cycle D and the boost ratio B.

In the reverse buck-boost mode (D<0.5), the output voltage and the input voltage are in reversal phase, and the output voltage can be higher or lower than the input voltage, it can be applied to the soft start of the motor. When the duty-ratio D is small, the boost ratio B is low; the output voltage is small and it is suitable for the low voltage starting of the motor. When the duty-ratio D is about 0.34, the boost ratio B=1, the output voltage will equal to the input voltage, the motor can operate in its rated mode. When the input voltage is low due to the power grid, the duty cycle D can be increased to more than 0.34, and the rated voltage of the motor can be achieved.

In the forward boost mode (D>0.5), the output voltage is in phase with the input voltage, and the boost function can be achieved, thus the sagged input voltage can be boosted. When the duty ratio D varies from 1 to 0.6, the boost ratio can be

continuously adjusted from B=1 to B=3, and the range of ac regulation is wide, it has good controllability, and the voltage can be continuously adjusted.

C. The Small Signal Model of The Converter

In order to investigate the dynamic performance of the presented converter, a small signal model is established, as shown in Fig. 7. Without considering the series resistance and the parasitic resistance of the inductor in the circuit, the load current is set to I_0 , $C_1=C_2=C$, $L_1=L_2=L$.



(a) The small signal model when in the operating state one



(b) The small signal model when in the operating state two Fig.7. The small signal model of the three-phase Z-source ac-ac converter.

The state equation of the circuit when it operates in the working state one can be obtained from Fig. 7(a):

$$\begin{bmatrix} di_{L1} / dt \\ di_{L2} / dt \\ dv_{C1} / dt \\ dv_{C2} / dt \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L} & 0 \\ 0 & 0 & 0 & \frac{1}{L} \\ \frac{1}{C} & 0 & 0 & 0 \\ 0 & -\frac{1}{C} & 0 & 0 \end{bmatrix} \times \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} \frac{v_i}{L} \\ 0 \\ -\frac{i_o}{C} \\ \frac{i_o}{C} \end{bmatrix}$$
(4)

The state equation of the circuit when it operates in the working state two can be obtained from Fig. 7(b)

$$\begin{bmatrix} di_{L1} / dt \\ di_{L2} / dt \\ dv_{C1} / dt \\ dv_{C2} / dt \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & -\frac{1}{L} \\ 0 & 0 & \frac{1}{L} & 0 \\ 0 & -\frac{1}{C} & 0 & 0 \\ \frac{1}{C} & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} \frac{v_i}{L} \\ 0 \\ 0 \\ 0 \end{bmatrix} (5)$$

Then we have

$$\begin{bmatrix} di_{L1}/dt \\ di_{L2}/dt \\ dv_{C1}/dt \\ dv_{C2}/dt \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{D}{L} & -\frac{1-D}{L} \\ 0 & 0 & \frac{1-D}{L} & \frac{D}{L} \\ \frac{D}{C} & -\frac{1-D}{C} & 0 & 0 \\ \frac{1-D}{C} & -\frac{D}{C} & 0 & 0 \end{bmatrix} \times \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} \frac{v_i}{L} \\ 0 \\ -D\frac{i_o}{C} \\ D\frac{i_o}{C} \end{bmatrix} (6)$$

By Laplace transform, the final small signal model equation of the system can be obtained by simplification.

$$\frac{v_C(s)}{D(s)} = \frac{(2I_L - I_o)Ls + v_i + (2v_C - v_i)(1 - 2D)}{LCs^2 + (-2D^2 + 2D - 1)}$$
(7)

III. THE SIMULATION RESULTS

The simulation parameters are given below: the frequency of the three-phase power supply is 50*Hz*, its peak voltage is 24*V*, the switching frequency is 10 *k*Hz, L_{x3} =300 μ H, L_{x1} = L_{x2} =500 μ H, C_{x1} = C_{x2} =4.7 μ F, C_{x3} =22 μ F, Z_{x3} =150 Ω +100 μ H (x=a, b, c).

A. The Instantaneous Potential Difference among The Common Node of The Load, The Neutral Point of The Three-phase Power Supply and The Switch S_{x2} (x=a, b, c)

In order to verify the above theoretical analysis, under the condition of the duty-ratio D=0.8, some simulations are performed with MATLAB and the potential difference between the neutral point of the three-phase power supply and the power switch S_{x2} (as shown in Fig. 8 (a)) is investigated, and the potential difference between the neutral point of the load and the power switch S_{x2} (as shown in Fig. 8 (b)) is also investigated.



Fig.8. The potential differences among the neutral point of the three -phase power supply, the power switch S_{x2} and the neutral point of the load.

From the simulation results shown in Fig. 9, when the power switches S_{x2} (x=a, b, c) is off, the potential of the neutral point of the three-phase power supply is basically equal to the potential of the neutral point of the load; When the power switches S_{x2} (x=a, b, c) is on, the potential of the neutral point of the three-phase power supply, the potential of the neutral point of the load and the potential at the power

switches S_{x2} (x=a, b, c) are basically equal, and these simulation results verify the above theoretical analysis.

B. The Output Voltages at Constant Duty Cycle

To verify the relationship between the duty ratio D and the boost ratio B, the input and output voltages of phase A and the three-phase voltage waveforms at different duty cycles of 0.2, 0.34 and 0.8 are simulated, respectively, as shown in Fig. 9.

According to the formula (3), when the duty cycle D is 0.8, 0.2, and 0.34, respectively, the peak value of the output voltage is 8V, 24V and 32V, respectively. The simulation results are very close to the theoretical value. When the duty cycle is D=0.2 and D=0.34, the output voltage is reverse-phase to the input voltage, as shown in Fig. 9 (a), (c), and when the duty cycle is D=0.8, the output voltage is in-phase to the input voltage, as shown in Fig. 9 (e). The simulation results also verify the theoretical analysis. As shown in Fig. 9 (b), (d), (f), the three-phase output voltage can be stable when the input voltage varying and this shows the continuous regulation controllability and the stability of the output voltage.





Fig.9. The input and the output voltage waveforms under different duty cycles: (a) - (f).

C. The Output Voltage When the Duty-Ratio Changes

In order to verify the dynamic performance of the three-phase output voltages when the duty-ratio changes, several time points are chosen, and at these time points allow the duty-ratio D to vary rapidly or slowly, as shown in table 1. The corresponding simulation results are shown in Fig. 10.

I ABLE I The Relationship Between Time <i>t</i> And Duty Ratio <i>D</i>					
T/(s)	0	0.1	0.2	0.3	0.4
$D_{l}/(\%)$	5	6	7	8	9
D ₂ / (%)	5	10	15	20	25

From the simulation results shown in Fig. 10, either varies the duty-ratio slow or fast, the output voltage waveforms can keep good smoothness, this implies the good dynamic characteristics of the presented circuit topology. Of course, when the duty-ratio D changes fast, the output voltages will include more harmonics, and it will pollute the power supply and do harm to the load, as shown in Fig. 10(b); and when the duty-ratio changes slowly, the waveforms of the output voltages will be better and this will be benefit to the load, as shown in Fig. 10(a).

D. The Output Voltage Recovery when in-phase Voltage sages

To verify the forward voltage sag recovery characteristic, the simulations are performed by adjusting the duty cycle D when the input voltage sags, and the simulation results are shown in Fig. 11.





(b) The output voltage waveforms when the duty ratio varies fast





(a) The waveforms of the input and the output voltage when the input voltage sags (phase A)



(b) The three-phase output voltage waveforms when the input voltage sags. Fig. 11. The output voltage waveforms when the input voltage sags.

According to Fig. 11 (a) and (b), in the positive boost mode (D>0.5), at a certain time when the input voltage is sagged (t=0.2s), by adjusting the duty ratio (t=0.3s, D from 1 to 0.77), the output voltages are restored to their original values and the voltage stability is achieved in a short time, this also shows the good dynamic characteristics of the circuit.

IV. EXPERIMENTAL RESULTS

According to the simulation results, the experimental circuit is established, as shown in Fig. 12. Adjust the three-phase voltages to 24V (peak value), using DSP TMS320F2812 to produce 6 pairs of complementary PWM signals, the IGBT drivers come from the two Luomuyuan KA962D driver boards, and FGA25N120 IGBT are chosen as the main power switches. Some experiments are performed to verify the relationship between the input and the output voltages, and the experimental results of the output voltage of the phase A and the three-phases when D=0.2 and D=0.8 are achieved, as shown in Fig. 13.



Fig. 12. The experimental prototype of the circuit.



(a) The input voltage (blue line) and the output voltage (red line) waveforms at D=0.2 (phase A)



(b) The input voltage (blue line) and the output voltage (red line) waveforms at D=0.8 (phase A)



(a) The output three-phase voltage waveforms at D=0.2(phase A is orange line, phase B is blue line and phase C is green line)



(d) The output three-phase voltage waveforms at D=0.8(phase A is orange line, phase B is green line and phase C is blue line)

Fig. 13. The experimental results of different duty cycles.

Because there are energy storage components in the circuit, there is a certain phase difference between the input and the output voltage and due to the switch frequency is much higher than the power frequency, the phase difference between the input and the output voltage will be very small and could be negligible. As shown in Fig. 13 (c) (d), the phase of the three-phase output voltages is basically consistent with the simulation results and the theoretical analysis.

In order to verify the output voltage stability when the input voltage sags, the experiments are performed and the output voltage waveforms of phase A are measured. As shown in Fig. 14, at the moment of t_1 there has voltage sag in the input voltage, and then the output voltage decreases, by adjusting the duty cycle D, at the moment of t_2 the output voltage starts recover, and at the moment of t_3 the output voltage recovered, the adjusting process is quite quickly, which is basically consistent with the simulation results.



Fig. 14. The waveforms of the output voltage when the input voltage sags (phase A).

The experimental results show that the output voltage is basically the same as the theoretical value, and the simulation and experimental results verify the theoretical analysis.

V.CONCLUSIONS

In this paper, a three-phase voltage-fed quasi-Z-source AC-AC converter topology is presented and analyzed based on its single-phase version. The relationship between the output voltage and the input voltage is obtained by analyzing the working principle and working process of the circuit. The feasibility of the circuit is verified by the simulation and

experimental results.

The presented circuit topology which has two work mode, the reverse buck-boost mode (D<0.5) and the positive boost mode (D>0.5), and it will provide a new approach for the three-phase voltage regulation.

Obviously, this topology has bidirectional power conversion ability, when the position of the input and the output are swapped, it will operate normally, and since the ac-ac converter could be looked as an ac transformer, the voltage gain when the power flow is reversed will be the reciprocal of that of the topology this manuscript analyzed, and the operating process will be analyzed in the future manuscript.

REFERENCES

- Peng, F. Z. "Z-source inverter", in the proceedings of the 37th Industry Applications Annual Conference, IAS 2002, 2002, vol. 2, pp. 775 –781
- [2] Fangzheng Peng, Xupeng Fang, Bin Gu, et al. "Z-source converter", *Transactions of China Electrotechnical Society*, vol.19, no.2, pp. 47-51, 2004.
- [3] Xupeng Fang. "Research on the Z-source inverter". The doctoral dissertation of Zhejiang University, 2005.
- [4] Xupeng Fang, "Single-phase voltage-fed Z-Source AC/AC converter", *Power Electronics*, vol.40, no.6, pp. 96-97, 2006.
- [5] Xupeng Fang, Yulin Xu, Yao Chen, et al. "Single-phase voltage-fed Quasi-Z-source AC-AC converter". *Modern Electronics Technique*, vol.39, no.14, pp. 147-149+153, 2016.
- [6] He Liangzong, Duan Shanxu, Peng Fangzheng, "Novel family of quasi-Z-source AC/AC converter with safe-commutation", in Proceedings of IEEE Energy Conversion Congress and Exposition. Energy Conversion Innovation for a Clean Energy Future, ECCE 2011, pp. 1417-1422.
- [7] Nguyen Minh-Khai, Lim Young-Cheol, Kim Yong-Jae, "A modified single-phase quasi-Z-source ac-ac converter", *IEEE Transactions on Power Electronics*, vol. 27, no. 1, pp. 201-210, 2012.
- [8] Nguyen Minh-Khai, Jung Young-Gook, Lim Young-Cheol, "Single-phase AC-AC converter based on quasi-Z-source topology", *IEEE Transactions on Power Electronics*, vol. 25, no.8, pp. 2200-2210, 2010.
- [9] Nguyen Minh-Khai, Jung Young-Gook, Lim Young-Cheol, "Single-phase AC/AC converter based on quasi-Z-source topology", in Proceedings of IEEE ISIE 2009, IEEE International Symposium on Industrial Electronics, 2009, pp.261-265
- [10] Nguyen Minh-Khai, Jung Young-Gook, Lim Young-Cheol, Cha Duk-Guen, "Single-phase quasi-Z-source AC/AC converter", in Proceedings of 31st International Telecommunications Energy Conference INTELEC, INTELEC 2009, 2009, pp.1-5
- [11] Nguyen Minh-Khai, Jung Young-Gook, Lim Young-Cheol, "Single-phase quasi-Z-source AC-AC converter with safe-commutation strategy", in proceedings of 2010 International Power Electronics Conference - ECCE Asia, IPEC 2010, 2010, pp. 562-566
- [12] Ahmed, Hafiz Furqan, Cha Honnyong, Khan Ashraf Ali, "A single-phase quasi-Z-source AC-AC converter with high-frequency transformer isolation", in proceedings of 2016 IEEE 8th International Power Electronics and Motion Control Conference, IPEMC-ECCE Asia 2016, July 13, 2016, pp.1111-1115.
- [13] Oum Jun-Hyun, Jung Young-Gook, Lim Young-Cheol, Wu Yan-Jun, "Single-phase quasi Z-source AC-AC converter with a series connection of the output terminals", in *Proceedings of 2012 IEEE International Symposium on Industrial Electronics*, ISIE 2012, 2012, pp. 503-508.
- [14] BANAEI M.R, AHRABI R. R.,ELMI M., "Single-phase safe commutation trans-Z-source AC-AC converter", *IET Power Electronics*, vol. 8, no. 2, pp. 190-201, February 1, 2015.
- [15] Ellabban Omar, Abu-Rub Haitham, "Grid connected quasi-Z-Source direct matrix converter", in Proceedings of 39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013, 2013, pp.

798-803.

- [16] Liu Shuo, Ge Baoming, Jiang Xinjian, Abu-Rub Haitham, Peng Fang Z., "A novel indirect quasi-Z-source matrix converter applied to induction motor drives", in proceedings of 2013 IEEE Energy Conversion Congress and Exposition, ECCE 2013, 2013, pp. 2440-2444.
- [17] Liu Shuo, Ge Baoming, Jiang Xinjian, Abu-Rub Haitham, Peng Fang Zheng, "Simplified quasi-Z source indirect matrix converter", *International Journal of Circuit Theory and Applications*, vol. 43, no. 11, pp.1775-1793, November 2015.
- [18] Kaykhosravi A., Azli N.A., Khosravi, F., Najafi E., "The application of a quasi Z-source AC-AC converter in voltage sag mitigation", in proceedings of 2012 IEEE International Conference on Power and Energy, PECon 2012, 2012, pp. 548-552.
- [19] Yoo Dae-Hyun, Oum Jun-Hyun, Jung Young-Gook, Lim Young-Cheol, "A quasi Z-source AC-AC converter with a low DC voltage distribution capability operating as a power electronic transformer", *Transactions of the Korean Institute of Electrical Engineers*, vol. 63, no. 3, pp. 358-366, March 2014.
- [20] He Liangzong, Duan Shanxu, Peng Fangzheng, "Safe-commutation strategy for the novel family of quasi-Z-source AC-AC converter", *IEEE Transactions on Industrial Informatics*, vol. 9, no. 3, pp. 1538-1547, 2013.
- [21] Oum Jun-Hyun, Jung Young-Gook, Lim Young-Cheol, Choi Joon-Ho, "Dynamic voltage restorer (DVR) for 6.6[kV]/60[Hz] power distribution system using two quasi Z-Source AC-AC converters", *Transactions of the Korean Institute of Electrical Engineers*, vol. 61, no. 2, pp. 199-208, February 2012.
- [22] Lei Qin, Peng Fang Z., "Four quadrant voltage sag/swell compensation with interphase quasi-Z-source AC-AC topology", in Proceedings of 2011 26th Annual IEEE Applied Power Electronics Conference and Exposition, APEC 2011, 2011, pp. 2013-2019.
- [23] Siwakoti Yam P., Blaabjerg Frede, Loh Poh Chiang, "New Magnetically Coupled Impedance (Z-) Source Networks", *IEEE Transactions on Power Electronics*, vol.31, no. 11, pp. 7419-7435, November 2016.



Xupeng Fang was born in Shandong Province, China, in 1971. He received the B.S. and M.S. degrees from the Shandong University of Science and Technology of China, Qingdao, in 1994 and 1997, respectively, majored in industry automation, electrical drive and its automation, respectively, and the Ph.D.

degree from the Zhejiang University of China, Hangzhou, in 2005, in electrical engineering. He joined the Shandong University of Science and Technology, Qingdao, China, in 1997 and now he is an Associate Professor in the College of Electrical Engineering and Automation. He was a visiting scholar in the Power electronics and Motor drive center of Michigan State University from March, 2013 to March, 2014. He has published over 90 papers, wherein includes over 30 papers in IEEE Transactions and IEEE conference proceedings, and held 14 patents, and has applied for 2 invention patents that in the examination stage. His research interests include Z-source converter and its applications, utility applications of power electronics such as active filters and FACTs devices, renewable resources generation. Dr. Fang is a senior member of China Electrotechnical Society Power Electronics Society and an invited reviewer of IEEE Transactions on Power Electronics, IEEE Transactions on Industrial Electronics, IEEE Transactions on Circuits and Systems, IEEE Transactions on Transportation Electrification

and Transactions of China Electrotechnical Society.



Guanzhong Gao was born in Shandong Province, China, in 1993. He received the B.S. from the Shandong University of Agricultural of China, Taian, in 2016, majored in electrical engineering and its automation, and now he is pursuing his Master's degree in the Shandong University of Science and Technology, majored in electrical engineering.



Lixin Gao was born in Shandong Province, China, in 1992. She received the B.S. from the Shandong University of Agricultural of China, Taian, in 2015, majored in electrical engineering and its automation, and now she is pursuing her Master's degree in the Shandong University of Science and Technology, majored in electrical engineering. B.S. degree from the Shengli College of China University of Petroleum, Dongying, in 2015, majored in electrical engineering and its automation, and now he is pursuing his Master's degree in the Shandong University of Science and Technology, majored in electrical engineering.



Bolong Ma was born in Shandong Province, China, in 1984. He received the